Chin. J. Astron. Astrophys. Vol. 6 (2006), **Suppl. 2**, 74–80
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

A Generic Pulsar Radio Emission Mechanism

D. B. Melrose *

School of Physics, University of Sydney, NSW 2006, Australia

Abstract A generic interpretation of pulsar radio emission that does not rely on the identification of a specific emission mechanism is explored. Coherence is quantified in terms of a coherence factor, which implies a maximum brightness temperature; the possible significance of Poincaré invariants is pointed out, and the potential use of higher order moments of the intensity to measure the coherence is discussed. The effect of the Lorentz boost between the plasma rest frame and the pulsar frame, the suppression of emission at low frequencies due to curvature of the field lines, and a natural frequency of the pulsar plasma are incorporated into a generic model for pulsar emission, and three illustrative examples of its possible use are given.

Key words: pulsars: general — radio continuum: stars

1 INTRODUCTION

After nearly four decades since the discovery of radio pulsars we have not identified the pulsar radio emission mechanism unambiguously. On the one hand, this failure might be thought surprising. There is an enormous body of observational data on radio pulsars, allowing statistical studies as a function of the pulse period (P) and period derivative ($\dot{P}$), and quantities derived from them (the age $\propto P/\dot{P}$ and the magnetic field strength $\propto (P\dot{P})^{1/2}$), (e.g. Graham-Smith 2003). The radio emission of most pulsars has some obvious common features: a relatively narrow frequency range, $\sim 100\,\mathrm{MHz}$ to $\sim 10\,\mathrm{GHz}$ (despite the wide range of $P, \dot{P}$), very high brightness temperature $T_{\rm b}$, and high degree of polarization with a characteristic sweep of position angle (PA) and strong evidence for escape in two orthogonally polarized modes (OPMs) (McKinnon & Stinebring 2000). These common features suggest an emission mechanism with robust features that applies to all radio pulsars. One might expect it to be straightforward to identify the most favorable emission mechanism by comparing the predicted properties for each suggested mechanism with the observed properties. On the other hand, the difficulties encountered in making such comparison provide an obvious explanation as to why no consensus on a specific emission mechanism has emerged. On the observational side, while there are many common observational features of pulsars, there is also a remarkable individuality among them. There are exceptions to virtually every rule proposed in summarizing the properties of pulsar radio emission, and each exception requires a specific explanation, greatly complicating the identification of specific constraints to impose on an acceptable emission mechanism. On the theoretical side, there are uncertainties in the modelling of the pulsar magnetospheres. For example, recently it has been suggested (Levinson et al. 2005; Melrose et al. 2005) that models based on electrostatic screening above a pair formation front may be unstable and that the screening is inductive involving oscillatory motions of the electrons and positrons, as suggested by Sturrock (1971); moreover, a prediction of downward emission, as well as upward emission, has observational support (Dyks, Zhang & Gil 2005). Such uncertainties leave us in a vicious circle: we need to identify the emission mechanism in order to use the radio data to constrain the models of the magnetosphere, and we need to use a model of the magnetosphere to constrain the emission mechanism in order to interpret the radio data. Moreover, any acceptable emission mechanism

$\star$ E-mail: `melrose@physics.usyd.edu.au`

must be ‘coherent’ in the sense that it involves some form of instability, and our understanding of coherence and of coherent emission in astrophysical plasmas is far from complete. A particularly serious difficulty in identifying a specific mechanism is that many of the features of the predicted emission can be attributed to generic properties of emission by highly relativistic electrons (or positrons) moving in one dimension along curved field lines; because these features are common to effectively all emission mechanisms they cannot be used to distinguish between different emission mechanisms. Similarly, to the extent that the polarization is determined by propagation effects, as suggested by the OPMs, it can also be regarded as generic, rather than associated with a specific emission mechanism.

In this paper, a different approach is suggested: an attempt is made to circumvent identification of a specific emission mechanism. Instead of viewing the common features, such as those mentioned above, as difficulties impeding the identification of a specific mechanism, they are regarded as the basis for a generic emission mechanism. The idea is to rely on general assumptions about the pulsar magnetosphere, the source region and the emission mechanism to infer the generic properties of any acceptable emission mechanism. Certain general assumptions are needed to constrain the possibilities, and general assumptions made here include:

1. The very high brightness temperature is due to an instability in which the growing waves can either (a) escape directly, or (b) be partially converted into escaping radiation due to nonlinear effects or inhomogeneities.
2. The emission is generated above the polar cap regions of a pulsar in a pair plasma that is flowing at a bulk relativistic speed along curved field lines.
3. The theory of wave dispersion in a pulsar plasma implies that there are two approximately transverse wave modes above some characteristic frequency, and the radiation is assumed to escape in a mixture of these two natural wave modes.

The first of these assumptions involves the general question of coherence and coherent emission, and these are discussed in Section 2. The second assumption is discussed in terms of quantities that can be inferred directly from observations, that is, quantities that are constants along a ray (Section 3) and Lorentz invariants that have the same values in both the rest frame of the plasma and in the pulsar frame (Section 4). The effects of curvature of the field lines and of wave dispersion in a pulsar plasma are discussed in Section 4. The conclusions are presented in Section 5.

2 COHERENCE

A characteristic feature of pulsar radio emission is its very high brightness temperature, which implies that the emission process must be coherent. The brightness temperatures estimated are typically $T_{\rm b} > 10^{25}\,$K, with the most extreme case known being for the giant pulses in the Crab (Hankins 1996), $T_{\rm b} \approx 10^{36}$–$10^{39}\,$K. Besides $T_{\rm b}$, there are other measures of the coherence that should be explored, but little or no observational data is available on these potential measures.

2.1 Coherence Time

The measured coherence time of a signal cannot be longer than the inverse of the bandwidth over which it is measured: the product of the time scale and the bandwidth of observation is limited by the Nyquist criterion. It is assumed here that measurements are made under idealized conditions at this limit. Measurement of the coherence time, $t_{\rm c}$, then provides information about the coherence of the emission process.

Given a sequence of measurements of the intensity, $I(t)$, one can construct the structure function

$$\langle I^2\rangle(t) = \langle [I(t'+t) - I(t')]^2\rangle, \tag{1}$$

where the average, denoted by the angular brackets, is over the time t'. All structure functions must increase from zero at $t = 0$ to a constant value ($2\langle I^2\rangle$ here) for large t. The characteristic time over which the constant value is approached is the coherence time. Typically in astrophysical contexts, the rise has a power-law form for $t \ll t_{\rm c}$, and the power-law index is a measurable quantity that can provide information on the mechanism producing the coherence. An attempt has been made to measure the coherence of pulsar radio emission (Jenet, Anderson & Prince 2001), but the interpretation is uncertain (Smits et al. 2003).

2.2 Probability Distribution Function for the Intensity

A coherence-related quantity that is measurable in principle is the probability distribution function (PDF) for the intensity, $p(I)$, where $p(I)dI$ be the probability of measuring an intensity between I and $I + dI$. This probability for $t \gg t_{\rm c}$ has already provided useful information on the properties of pulsar radio emission (Cairns, Johnston & Das 2004), but this is not relevant here. The discussion here applies only to measurements for $t < t_{\rm c}$, when $p(I)$ contains information on the coherence properties.

The quantities that can be measured are the moments of $p(I)$,

$$\langle I^n \rangle = \int_0^\infty dI\, I^n\, p(I), \tag{2}$$

with $n \geq 1$ an integer. The first moment, $n = 1$, defines the mean intensity, and contains no information on the state of coherence. The second moment, $n = 2$, does contain information on the state of coherence. Measuring all moments is effectively equivalent to measuring $p(I)$.

Two opposite idealized cases for $p(I)$ are a completely coherent source, $p(I) = \delta(I - I_0)$, which has a well-defined intensity, I_0, and a 'thermal' source, which has an exponential PDF, $p(I) = \langle I \rangle^{-1} \exp(-I/\langle I \rangle)$. Note that 'thermal' does not imply a black-body spectrum, but implies only that the photon counting statistics are the same as for a thermal source. More complicated PDFs can be constructed by convolving idealized PDFs and including noise.

To illustrate the point, consider the moments (2) for the two idealized PDFs: one has $\langle I^n \rangle = \langle I \rangle^n$ for a completely coherent source, and $\langle I^n \rangle = n! \langle I \rangle^n$ for a 'thermal' source. Thus even measuring $\langle I^2 \rangle / \langle I \rangle^2$ would provide additional information on the coherence, and should distinguish between these two extreme cases. However, no observational information on $\langle I^2 \rangle / \langle I \rangle^2$ is available for pulsars.

2.3 Coherence Factor

A useful concept in a semi-quantitative discussion of coherent emission is coherence factor, $N_{\rm c}$, defined as the number of radiating particles per coherence volume, $V_{\rm c}$, with

$$\frac{1}{V_{\rm c}} = \int_{\mathcal{K}} \frac{d^3\boldsymbol{k}}{(2\pi)^3}, \tag{3}$$

where $\mathcal{K}$ is the region of $\boldsymbol{k}$-space to which the radiation is confined. An observational limit on N_c arises from the requirement that the energy in the radiation in a coherence volume not exceed the energy in the radiating particles. With $k_B T_{\rm b}/V_{\rm c}$ the energy density in the radiation, $k_B T_{\rm b}$ is the energy in the radiation in a coherence volume (k_B is Boltzmann's constant). For radiating particles with a Lorentz factor γ, this constraint requires

$$T_{\rm b} < T_{\rm max}, \qquad T_{\rm max} = N_{\rm c}(\gamma - 1)\frac{mc^2}{k_B} = N_{\rm c}(\gamma - 1)\, 0.5 \times 10^{10}\,{\rm K}. \tag{4}$$

For example, with $\gamma \approx 10$, one requires $N_{\rm c} > 10^{14}$ to account for $T_{\rm b} = 10^{25}\,{\rm K}$ in a typical pulsar, and $N_{\rm c} > 10^{28}$ to account for $T_{\rm b} = 10^{39}\,{\rm K}$ in the most extreme of the Crab's giant pulses.

3 RELATING OBSERVED QUANTITIES TO THEIR SOURCE

Two classes of physical quantities are particularly useful in relating the pulsar emission process to the properties of the observed radiation: constants along a ray and invariants. Constant along the ray path include the frequency and the brightness temperature. The wave vector, $\boldsymbol{k}$, is not constant and varies as a result of refraction, which can affect the shape of the spectrum (Petrova 2002). An important example of a quantity that is both a constant along a ray and a Lorentz invariant is the occupation number of the wave quanta, $N(\boldsymbol{k}) = k_B T_{\rm b}/\hbar\omega$. Less familiar examples are the Poincaré invariants which are also constant along a ray and invariants.

3.1 Poincaré Invariants

The Poincaré invariants are related to Liouville's theorem. A statistical distribution of wave quanta is analogous to a statistical distribution of particles, and Liouville's theorem applies in the same way to both. The product of the occupation number and the extension in phase is the number of wave quanta in a given region of phase space, and in the absence of emission and absorption this number is an invariant. Liouville's theorem implies that both the distribution function and the extension in phase are separately invariant. Thus, beside the invariance of the occupation number, the extension in phase is invariant. Using 3, conservation of extension in phase implies that

$$\frac{\delta V}{V_{\rm c}} = \int_{\mathcal{K}} \frac{d^3x d^3\boldsymbol{k}}{(2\pi)^3}, \tag{5}$$

is an invariant. The one-dimensional counterpart along the direction of $\boldsymbol{k}$ is also an invariant, and this is equal to the ratio of the length, ΔL, of the beam of radiation to the coherence length, $L_{\rm c} \approx 1/\Delta k_z$, where $\Delta k_z \approx \Delta\omega/c$ is the range of wave numbers. One may write $\Delta V = \Delta L\, \Delta A$ and $V_{\rm c} = L_{\rm c} A_{\rm c}$, and then the invariance of $\Delta V/V_{\rm c}$ and of $\Delta L/L_{\rm c}$ together imply the invariance of $\Delta A/A_{\rm c}$, which is sometimes called the generalized étendue. The generalized étendue implies that for a bundle of rays that fills a solid angle $\Delta\Omega$ and an area ΔA normal to the ray direction, the product $|\boldsymbol{k}|^2 \Delta A\, \Delta\Omega$ is conserved along a ray and is also an invariant. These one-, two- and three-dimensional extensions in phase are the Poincaré invariants. Measurement of them at the point of observation gives direct information of them in the source region.

3.2 Lorentz Transformations

In a standard model in which the radio emission is generated in a relativistically outflowing pair plasma, it can be useful to treat the emission of the radiation in the rest frame of the plasma, and then to Lorentz transform to the pulsar frame. Some of the characteristic properties of the observed radiation may be attributed to this Lorentz transformation.

Consider a Lorentz boost between a primed frame, identified as the rest frame of the plasma, and an unprimed frame, identified as the observer's frame, in which the plasma has bulk velocity U along the z-axis, with $\Gamma = 1/(1 - U^2/c^2)^{1/2}$. The frequency transforms as $\omega = \Gamma(\omega' + k'_z U)$, the wavenumber along the direction of the boost transforms as $k_z = \Gamma(k'_z + \omega' U/c^2)$, and the wavenumber perpendicular to this direction is unchanged, $k_\perp = k'_\perp$. This inverse transform follows by interchanging primed and unprimed quantities, and replacing U by $-U$.

In the rest frame of the plasma, the random motions of the particles is still highly relativistic, but is roughly symmetric between the forward and backward directions. Depending on the details of the specific emission mechanism, one might expect emission to favor the forward and backward directions, or the perpendicular (to the magnetic field) direction. The effects of the Lorentz boost on these cases may be approximated relatively simply, provided two conditions are satisfied: the refractive index is close to unity, and the angle of propagation is not too close to the backward emission in the rest frame. Then, on writing $k'_z = (n'\omega'/c)\cos\theta'$, and similarly for the unprimed variables, except for a range of angles $\approx 1/\Gamma$ around backward propagation ($\theta' = \pi$) in the rest frame, one has

$$\frac{\omega}{\omega'} \approx 2\Gamma \cos^2(\theta'/2), \qquad \tan\theta \approx \frac{\tan(\theta'/2)}{\Gamma}, \tag{6}$$

where $n' \approx 1$, $U/c \approx 1$ are assumed. From this approximation one infers the following properties:

1. Forward emission ($\theta' < \pi/2$) in the rest frame is boosted in frequency by a factor between $\omega/\omega' = \Gamma$ and 2Γ, and is confined to a forward cone $\theta < 1/\Gamma$.
2. Approximately perpendicular emission ($\theta' \approx \pi/2$) in the rest frame is boosted in frequency by a factor $\approx \Gamma$, and is concentrated around the cone $\theta < 1/\Gamma$.
3. Most backward ($\theta' > \pi/2$) emission in the rest frame is boosted in frequency by a factor $< \Gamma$, and is in the forward direction at $1/\Gamma < \theta < \pi/2$.
4. Only emission nearly in the backward direction ($\pi - \theta' < 1/\Gamma$) in the rest frame remains in the backward direction ($\theta > \pi/2$) in the pulsar frame.

An important qualitative point is that the observed radiation could plausibly include radiation emitted in the backward direction in the rest frame, and that its properties differ in relatively subtle ways from those of radiation emitted in the forward direction in the rest frame.

4 LOW FREQUENCY LIMITS ON THE EMISSION

The lowest frequency of the observed emission can be used to put constraints on the emission mechanism due to two effects: curvature of the field lines and the plasma dispersion properties.

4.1 Curvature Emission at Low Frequencies

Irrespective of the actual emission mechanism, the low-frequency emission must be dominated by the effects of curvature of the field lines (Q. Luo, private communication 2004), as may be understood from the following argument (cf. Melrose 1978). Consider a relativistic particle, with Lorentz factor γ, moving along a field line with radius of curvature $R_{\rm c}$. Its emission is confined to a forward cone with half angle $\sim 1/\gamma$, and an observer must be on a line of sight within an angle $\sim 1/\gamma$ of the direction of the magnetic field line to see it. The cone of emission by the particle intersects the line of sight to the observer only for a time $\Delta t \sim 2\pi R_{\rm c}/c\gamma$, and then the particle is traveling nearly towards the observer, so that the pulse of radiation received by the observer is shortened by a factor $\sim 1/2\gamma^2$. The typical frequency, $\omega_{\rm c}$, of curvature emission is identified by equating $2\pi/\omega_{\rm c}$ to the duration of the pulse of radiation received by the observer. This gives $\omega_{\rm c} = \pi c\gamma^3/R_{\rm c}$. Curvature emission is restricted to $\omega \lesssim \omega_{\rm c}$. Now consider this same argument applied to any other emission process other than curvature emission itself. The curvature of the field lines implies that in the pulsar frame the emission at $\omega < \Omega_{\rm c}$, with

$$\Omega_{\rm c} = \frac{\pi c\Gamma^3}{R_{\rm c}}, \tag{7}$$

must be dominated by the effects of curvature. The postulated coherent emission can be observed only at high frequencies, $\omega > \Omega_{\rm c}$, where it is not obscured by the effects of curvature. Hence, $\Omega_{\rm c}$ may be interpreted as a low-frequency cutoff for the coherent emission. This cutoff frequency is

$$\omega_{\rm min}/2\pi = (150\,{\rm MHz})\left(\frac{\Gamma}{10^2}\right)^3\left(\frac{R_{\rm c}}{10^6\,{\rm m}}\right)^{-1}. \tag{8}$$

An exception is if the emission mechanism is due to maser curvature emission (Luo & Melrose 1992, 1995), which has characteristic frequency $\omega_{\rm c}$.

4.2 Low Frequency Limit for OPMs

The observation of OPMs requires that the radiation propagate in two orthogonal modes. There is a characteristic frequency above which the wave modes of the plasma have refractive indices close to unity and nearly transverse polarization, and below this frequency the modes do not satisfy these conditions. This frequency is characteristic of so-called relativistic plasma emission (RPE) (Melrose & Gedalin 1999) and is given by

$$\omega_{\rm RPE}/2\pi \approx (10\,{\rm GHz})\left(\frac{B_*}{10^{12}\,{\rm G}}\right)^{1/2}\left(\frac{P}{100\,{\rm ms}}\right)^{-1/2}\left(\frac{r}{R_*}\right)^{-3/2}(M\langle\gamma'\rangle\Gamma)^{1/2}, \tag{9}$$

where B_* is the surface magnetic field, r is the emission height, R_* is the radius of the star, M is the pair multiplicity in terms of the Goldreaich-Julian density and $\langle\gamma'\rangle$ is the mean Lorentz factor of the particles in the rest frame. For the radiation to escape as a mixture of two OPMs it either needs to be generated near of above $\omega_{\rm RPE}$, or be generated in a single mode at a lower frequency and converted into a mixture of the two modes at a point along the ray where the condition $\omega > \omega_{\rm RPE}$ is satisfied.

5 GENERIC EMISSION MECHANISM

Rather than regard the generic features that are common to all emission mechanisms as limiting our ability to identify a specific mechanism, we may regard them as defining a generic pulsar radio emission mechanism. Such a generic mechanism, subject to the general assumptions made in the Introduction, includes the following features.

5.1 Features of a Generic Mechanism

Brightness temperature: The very high T_b implies a coherent emission process. There is a maximum possible T_b, given by (4). An observational determination of T_b places a constraint on the parameters in the emission region through (4).

Coherence factor: The coherence factor is an invariant equal to the number of radiating particles in a coherence volume. It may be estimated from observation, and used to constrain the emission process.

Lorentz boost: Bulk motion of the pair plasma at Lorentz factor Γ, implies that the observed frequency is boosted by $> \Gamma$ ($< \Gamma$) for forward (backward) emission in the rest frame.

Angular distribution: The observed emission can be due to either forward of backward emission in the rest frame, with these separated by the angle $\theta = 1/\Gamma$ in the pulsar frame.

Curvature cutoff: Curvature effects suppress the emission at $\omega < \Omega_\mathrm{c}$, cf. (7).

Polarization: The polarization appears to be dominated by two effects: the rotating vector model and propagation in two orthogonal modes. The rotating vector model determines the general sweep of linear polarization. Most other features of the polarization may be interpreted in terms of OPMs that propagate along different ray paths, with the observed polarization characteristic of a polarization limiting region. The theory of wave dispersion in a pulsar magnetosphere implies that the interpretation in terms of OPMs applies only if the emission is generated near or above the characteristic frequency (9).

5.2 Implications of a Generic Mechanism

For the concept of a generic emission mechanism to be useful one needs to be able to use it to draw useful conclusions from observational characteristics. Consider the following three examples. First, the low-frequency cutoff, ω_min, cf. (8), can be used to place a limit on the the bulk Lorentz factor and the radius of curvature of the field lines in the source region of the emission from any pulsar with an observed low-frequency cutoff. Moreover, the natural frequency ω_RPE, cf. (9), separates lower frequencies where any emission processes is likely to be strongly dependent on the plasma dispersion, from higher frequencies where the plasma dispersion should have little effect on the emission, with this frequency also be the natural frequency for relativistic plasma emission. By comparing ω_RPE and ω_min one can infer constraints on the emission mechanism in order to account for emission at the lowest frequency. Second, the effect of the Lorentz boost, from the rest frame of the plasma to the pulsar frame, on the frequency and angular distribution of the radiation has general implications that have not been investigated thoroughly. Any emission mechanism is likely to favor emission either parallel or perpendicular to the magnetic field in the rest frame, and parallel emission should be in both the forward and backward direction. On the basis of this, for example, one might speculate that core emission and conal emission are due to forward and backward emission in the rest frame. One could use inferences on the angular separation of core and conal emission to place a limit on Γ. Third, the implication of the extensive data on OPMs is that the radiation escapes as a mixture of two modes, and this requires that it either be generated as a mixture of two modes or be converted into a mixture of two modes as a propagation effect. Both suggestions encounter major difficulties. Maser emission mechanisms tend to favor the faster growing mode and emission should be essentially 100% in this mode, except under conditions that seem very difficult to satisfy (Melrose & Judge 2004). Separation into two natural modes as a propagation effect is ineffective, even in extremes cases such as the presence of sharp boundary, because one of the X mode has vacuum-like characteristics and is unaffected by any plasma inhomogeneity (Barnard & Arons 1986; Petrova 2001). Irrespective of these difficulties, the generic model implies that the mixture of modes must be generated in a region where the observed frequency satisfies $\omega \geq \omega_\mathrm{RPE}$.

6 DISCUSSION AND CONCLUSIONS

In this paper, two new ideas are suggested, and these need further development and refinement.

The first idea concerns the quantification and measurement of coherence. Coherence can be quantified in terms of a coherence factor equal to the number of radiating particles within a coherence volume. The coherence volume itself is related to a Poincaré invariant, and the possibility of using the generalized étendue (another Poincaré invariant) to infer properties in the source region is pointed out. This factor can be estimated from the brightness temperature, and used to place a limit on the properties of the plasma in the emission region, cf. (4). There are other measurable quantities related to the coherence of the radiation.

Specifically, measurement of higher moment of the intensity over very short time and frequency ranges can be used to used to distinguish between coherent and 'thermal' distributions, as discussed in Section 2.

The other idea is the concept of a generic emission mechanism, where one uses generic features that apply to any emission mechanism (or at least to broad classes of emission mechanism) to relate observed properties of the radiation to properties of the plasma in the source region. Particular features discussed include the coherence, the effect of a Lorentz boost between the plasma rest frame and the pulsar frame, a low-frequency cutoff due to curvature of the field lines, and the interpretation of the polarization in terms of OPMs. Three illustrative examples of the use of a generic model are discussed briefly: the interpretation of low-frequency cutoffs, the possible interpretation of core and conal emission in terms of Lorentz boosted forward and backward emission in the rest frame, and the required separation into two natural modes to account for the observed OPMs. The interpretation of the polarization as a propagation effect also suggests that polarization might be regarded as a generic effect, but this is not discussed specifically in this paper.

References

Barnard, J. J., Arons, J., 1986, ApJ, 302, 138
Cairns, I., Johnston, S., Das, P., 2004, MNRAS, 353, 270
Dyks, J., Zhang, B, Gil, J., 2005, ApJ, 626, L45
Graham-Smith, F., 2003, Rep. Prog. Phys. 66, 173
Hankins, T., 1996, in Johnston, S., Walker, M. A., Bailes, M., eds, ASP Conf. Ser. Vol. 105, Pulsars: Problems and Progress, San Francisco: ASP, p. 197
Jenet, F. A., Anderson, S. B., Prince, T. A., 2001, ApJ, 558, 302
Levinson, A., Melrose, D., Judge, A., Luo, Q., 2005, ApJ, 631, 456
Luo, Q., Melrose, D. B. 1992, MNRAS, 258, 616
Luo, Q., Melrose, D. B. 1995, MNRAS, 276, 631
McKinnon, M. M., Stinebring, D. R., 2000, ApJ, 529, 433
Melrose, D. B., 1978, ApJ, 225, 557
Melrose, D. B., Gedalin, M. E., 1999, ApJ, 521, 351
Melrose, D. B., Judge, A. C., 2004, Phys. Rev. E, 70, 056408
Melrose, D., Levinson, A., Judge, A., Luo, Q., 2005, in AIP Conf. Proc. 784, p. 174
Melrose, D. B., Luo, Q., 2004, Phys. Rev. E, 70, 016404
Petrova, S. A., 2001, A&A, 378, 883
Petrova, S. A., 2002, A&A, 383, 1067
Smits, J. M., Stappers,B.W., Macquart,J.-P., Ramachandran,R., Kuijpers,J., 2003, A&A, 405, 795
Stinebring, D. R., Cordes, J. M., Rankin, J. M., Weisberg, J. M., Boriakoff, V., 1984, ApJS, 55, 247
Sturrock, P. A., 1971, ApJ, 164, 529